Summary Report

Ensuring Quality Long-Term Monitoring with Geonor Precipitation Gauges

May 15 & 16, 2003
University of Colorado at Boulder
Boulder, Colorado

I. Introduction

Obtaining accurate precipitation measurements is a problem that has plagued scientists for centuries, and many challenges remain. For example, collecting snow and other solid precipitation poses a different set of difficulties than those involved in collecting liquid precipitation. In the mid-1980s, this need for better solid precipitation measurements gave rise to a new style of precipitation monitoring using a weighing bucket type gauge. In this system, precipitation is collected in a bucket supported by wires, which vibrate at different frequencies as the bucket becomes heavier. The frequency of vibration can be translated to an accumulation amount in the bucket. Major improvements associated with this style of monitoring precipitation include the following:

- the sensors are considerably better at monitoring solid precipitation;
- the sensors are considerably better at measuring very light rates of precipitation; and
- the sensors are capable of measuring very high rates of precipitation as long as the bucket does not overflow.

Weighing bucket types gauges manufactured by Geonor are being used in a number of national networks, particularly in Canada and in the Scandinavian countries. The U.S. Climate Reference Network (USCRN), with 27 sites currently in operation and a planned total of 221 stations, is also using the Geonor gauge. The weighing bucket style of monitoring is now accumulating its own substantial history and is expected to play an increasingly important role in the future of precipitation monitoring.

As with all measurement systems, some outstanding issues remain with regard to operating and obtaining quality data from the instruments. These issues led to the organization of a workshop held in Boulder, Colorado, in May 2003. The workshop was convened by Dr. Betsy Weatherhead to provide a forum for discussing issues related to using weighing bucket type gauges for precipitation monitoring. The decision to organize the workshop arose from Dr. Weatherhead's discussions with the World Meteorological Organization (WMO) concerning challenges arising in long-term climate monitoring. The goal of the workshop was to address several issues pertinent to the long-term network operation of Geonor precipitation gauges. Topics discussed include the use of antifreeze and oil, sampling frequencies, snow-capping, wind undercatch, wire breakage, quality assessment, and other issues relevant to long-term, high-quality measurements.

Among the topics discussed was the importance of adequate wind shielding in any attempt to obtain quality precipitation measurements. All precipitation measurements are affected by local winds, which can cause an undercatch effect. Different wind shields have been developed and tested and are found to perform differently in reducing the amount of undercatch. Minimizing and correcting the undercatch effects are critical for both climatological understanding and real-time monitoring.

II. Participation

The two-day workshop brought together scientists and engineers involved in precipitation measurement and analysis. Representatives from the Swedish Meteorological and Hydrological Institute, Environment Canada, and the U.S. Climate Reference Network (USCRN) attended the workshop, along with technical personnel from Geonor and from Campbell Scientific (responsible for the datalogger used with the Geonor). In addition, some representatives from the user community, particularly those interested in precipitation measurements at high latitudes, were in attendance. The complete attendee list and contact information are provided in Appendix 1.

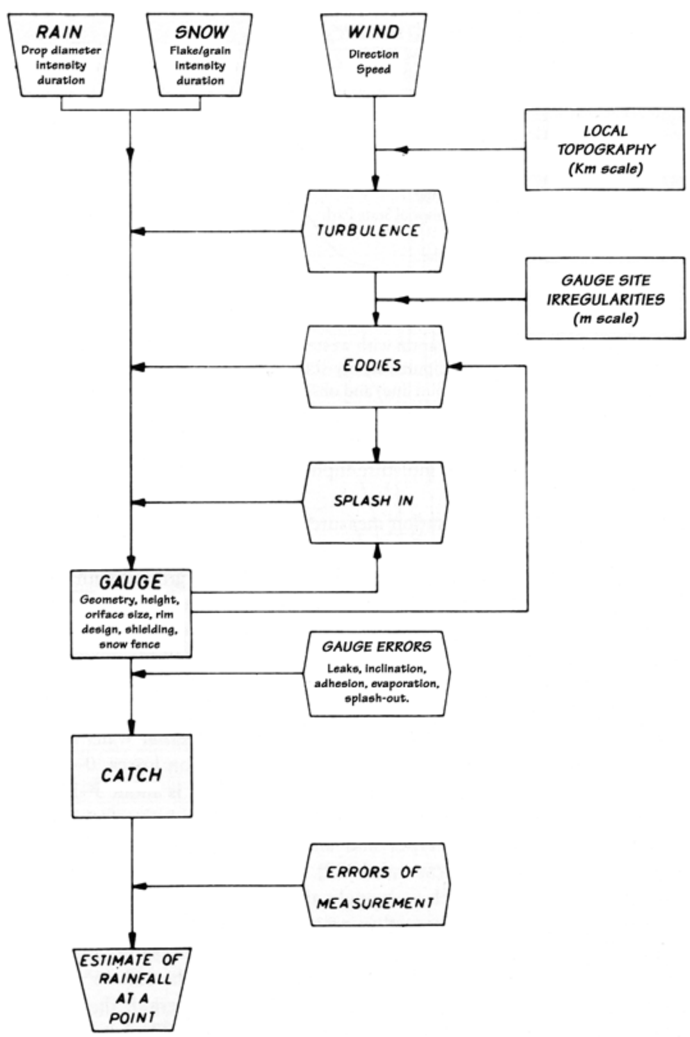
III. Opening of Workshop and Overview of Precipitation Measurements

Betsy Weatherhead opened the workshop with a brief overview of the agenda and objectives. First on the agenda for Day 1 were talks providing an overview of precipitation measurements and their applications. Second were overviews describing the weighing bucket approach used for precipitation measurements in networks in Sweden, Canada, and the U.S. An overview of the Geonor instrument used in these networks was next on the agenda, followed by individual studies focusing on aspects of the Geonor measurements and possible errors. The talks were followed by an optional trip to the Marshall test site where six Geonor gauges are currently being compared in different wind shield configurations. Roundtable discussions occurred during Day 2 to identify current needs and recommendations for issues pertinent to the long-term network operation of Geonor precipitation gauges.

One common theme that came up in many discussions was the idea that while some variables have a definite truth, for precipitation there are questions about what is a "truth" measurement. It is not clear what the answer to this question should be. “Truth” for precipitation corresponds to the actual amount that falls at a point over some time period. The exact amount may be unknowable, but we can estimate the truth by making measurements, and some measurements perform better than others. Daqing Yang (U. Alaska) made the statement that with reference gauges and appropriate wind shields, and perhaps some automated gauges, it is possible to improve the accuracy of precipitation observations. The WMO-recommended DFIR and pit gauges are the references for snow and rainfall observations, and provide measurements that are considered to be very close to the truth. These gauges have been found to be more accurate than most national standard gauge observations.

Roger Barry (NSIDC) presented an overview of precipitation measurements and error sources from his perspective analyzing precipitation data at high latitudes and high altitudes. He made a statement indicating that although people have been trying to measure precipitation for several centuries, we're still not able to do it well. The first gauges were designed in England in the 17th century (see figure in "Weather" Apr 2003, 58(4) p.138). The amount of precipitation reaching a gauge is affected by many factors, including large-scale turbulence, eddies over the gauge, rim design, splash-in/out and evaporation. Understanding and adjusting for these factors is essential to obtaining accurate measurements. Adjustment procedures rely heavily on wind speed measurements at gauge height during precipitation events. Formulae have been developed in several countries, particularly Switzerland (B. Sevruk), but wind tunnel studies of air flow over gauges of different design have only been performed for liquid precipitation. There are many different wind shield designs and several types and sizes of snow fences to use with a gauge. WMO has done intercomparison studies but more work in a variety of environments is needed. Introduction of new gauges, shields and measurement practices make obtaining homogeneous time series very difficult. Homogeneity can be absolutely impossible if agencies do not operate new systems alongside existing ones for at least one year. Roger pointed out that there is currently insufficient official recognition that precipitation amount and type are vital observations for long-term climate monitoring as specified through the Global Climate Observing System (GCOS), not just for short-term nowcasting and forecasting needs.

FACTORS AFFECTING PRECIPITATION GAUGE CATCH

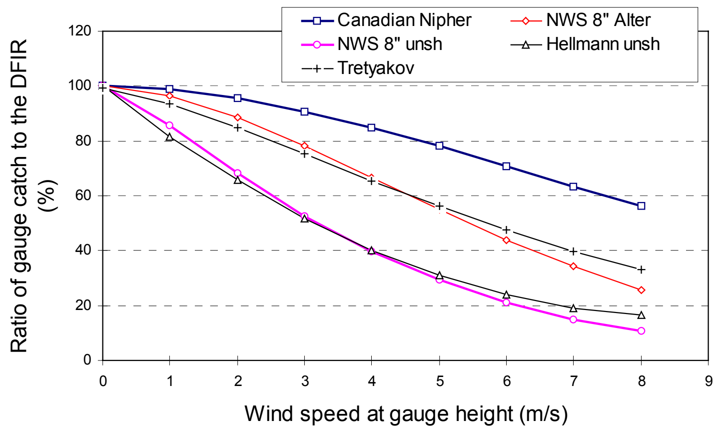


Factors affecting precipitation gauge catch. The amount of rainfall reaching a point is affected by a variety of atmospheric and other variables. The amount collected by a gauge is further affected by gauge characteristics and measurement errors. (From Roger Barry.)

Chuck Wade (NCAR) gave a talk on precipitation gauge studies at NCAR's Marshall field site and presented results from multiple gauge comparisons, including comparisons of six Geonor gauges. Because he is involved in efforts to provide precipitation rates for aviation icing applications, accurate real-time data are a critical concern. During his talk, he brought up the WMO recommendation that gauges not be heated because heating or over-heating can increase evaporative losses. The work of the NCAR group suggests that heating is necessary to preventing snow build-up that can interfere with precipitation collection. This topic would be revisited often during meeting discussions.

For all precipitation gauges, the amount of precipitation measured is strongly influenced by the local winds, requiring that most stations be surrounded by wind shields. Wind shield intercomparisons at NCAR's Marshall field site located outside Boulder, Colorado, are shown above. The results suggest that a full-size double fence intercomparison reference (DFIR) shield or a smaller (2/3 diameter) version of the DFIR will be most appropriate for achieving highest quality precipitation measurements. (From NCAR RAP.)

Daqing Yang (University of Alaska, Fairbanks) discussed precipitation measurements in cold regions and drew attention to the continuing need for intercomparisons and for overlap with conventional measurements to obtain climate quality data. He has been involved in World Climate Research Programme (WCRP) workshops to investigate the impact of automated precipitation measurements on the overall quality assurance/quality control of the data and is very involved in efforts to obtain climate quality data in the Arctic. He has also worked with Japan Frontier Research for Global Change and NOAA's Climate Monitoring and Diagnostics Laboratory (CMDL) on a gauge intercomparison at the Barrow CMDL/CRN site for last 3 years. Full-size DFIR, Wyoming snow fence, national standard gauges used in the arctic regions, and auto gauges were tested. The data and results will be useful for comparing and validating USCRN data collected in Alaska.

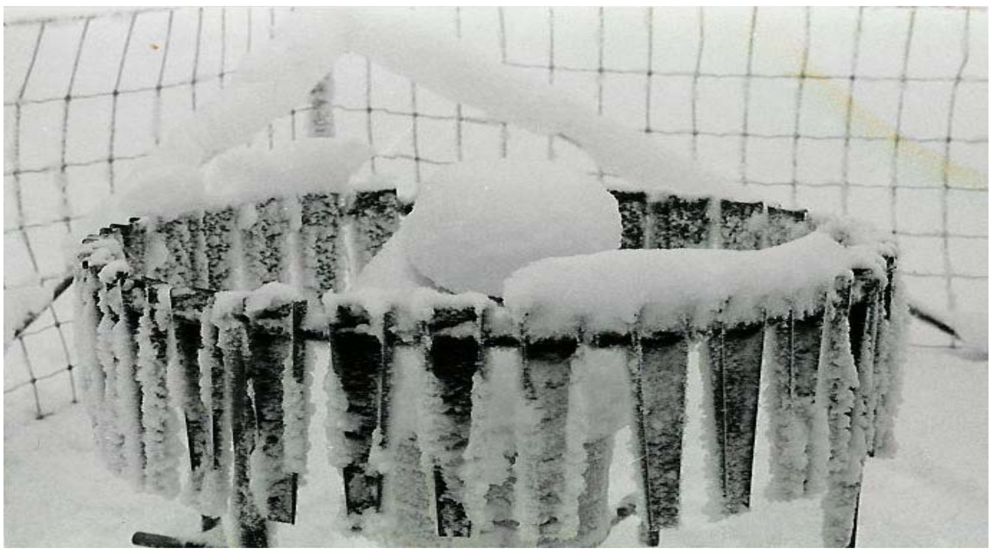


The amount of precipitation collected by a gauge is strongly affected by the wind shielding. Side-by-side comparisons of how much precipitation is measured using different shielding shows that some methods of monitoring will under-represent the amount of precipitation by as much as 80% relative to the DFIR. (From Daqing Yang.)

Betsy Weatherhead (CIRES/NOAA) gave a brief overview of the importance of reducing instrument uncertainty and showed some general circulation model projections that illustrate why understanding precipitation over the long term is important. A projected 5% increase in precipitation over land is expected over the next 100 years as a result of increasing greenhouse gases. The magnitude of this change is small and will require extremely accurate long-term measurements for verification.

IV. Network overviews

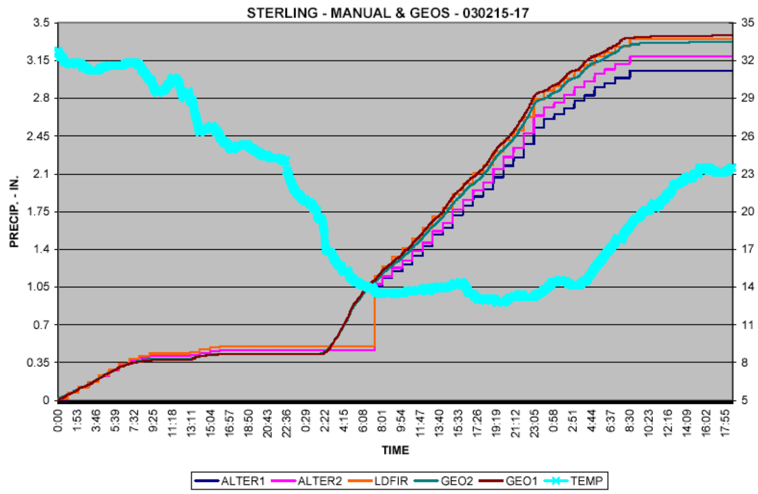
Ann-Christine Andersson and Sverker Hellström from the Swedish Meteorological and Hydrological Institute (SMHI) discussed precipitation measurements, maintenance, and quality assurance for 104 Geonor gauges used in Sweden's meteorological network. In seven years (7,052,000 network hours) of operation, they have had only five wire breaks on the Geonor gauges. All of the breakages were attributed to handling problems while emptying the bucket; no wires have broken during operation. The gauges are serviced annually each summer and are also emptied by the local maintenance person an additional one to two times per year. In analyzing the data, SMHI's quality control reports a sinusoidal-like daily variation that differs among stations. The variations in the signal are larger when the bucket is almost full and therefore heavy. Another unresolved problem they report is the general undercatchment of the Geonor gauge, typically only 50-80% of the amount measured by manual gauges. They are currently using a single-alter wind shield, but presented simulations showing that the air flow around the gauge is not uniform. They are also investigating adding heating to their gauges to reduce snow build-up problems. The SMHI network is well established and methods to ensure data quality are quite stable. For the great majority of the instruments, there have been no observed calibration changes during their seven years of operation. The calibrations performed in the laboratory and field match the calibrations supplied by the manufacturer to within the uncertainty in the calibration standards. Sverker reported on a correction algorithm defining a mathematical non-decreasing reference line around which the accumulated values are assumed to fluctuate. The precipitation amount during a given time period is set equal to the reference value at the end minus the reference value at the start of the period. In this way the monthly amount equals the sum of the daily amounts, and the daily amount equals the sum of the 24 hourly amounts. In the next version they will try to modify the algorithm to handle evaporation, in case it should occur despite the use of evaporation-preventing oil.



Snow-capping on a Geonor gauge. Build-ups of this type block precipitation from reaching the gauge inlet. This problem may require that the instrument be heated. Different methods of heating have been explored to try to prevent snow build-up without increasing precipitation loss due to evaporation. (From the Swedish Meteorological and Hydrological Institute.)

Yves Durocher (Environment Canada) gave an overview of Canada's Reference Climate Stations (RCS). Many of the stations already have more than a 30-year record so there is considerable effort to protect the network and ensure measurement continuity. The goal is to ultimately bring the network up to 298 stations and to fill every 5 x 5 degree grid. A formal board, the National Monitoring Change Management Board, exists to oversee any technological changes to the network. (Bruce Baker mentioned that there is a plan for a similar board for the USCRN.) Yves discussed decisions to use the Geonor gauges at the RCS sites and would address issues specific to the Geonor gauges in the network in a later talk.

Bruce Baker (National Climatic Data Center) gave an overview of the U.S. Climate Reference Network (USCRN). If fully implemented, the network will consist of 221 stations nationwide. There are currently 27 stations in operation. Among the USCRN's goals is the measurement of both liquid and solid precipitation. Comparisons with other gauges (including the Ott) were used to determine the best possible gauge to use. The Ott was found to report only about 95% of the precipitation reported by Geonor gauges, and a three-wire modification of the Geonor gauge is currently in use at the USCRN sites. An experiment in Bondville, Illinois, is currently underway to evaluate wind flow inside the shields and to better characterize the gauge-shield system.

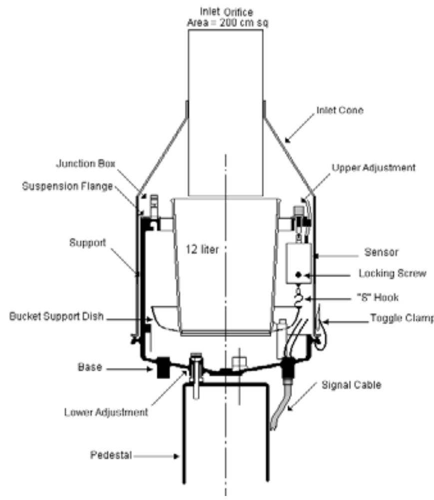


Results from gauge and wind shield intercomparisons at Sterling, Virginia, for a two-day precipitation event. The results show that the DFIR wind shielding performs well. (From Bruce Baker.)

V. Instrument overview

Øyvind Klevar (Geonor Norway) and Ed Brylawski (Geonor U.S.) talked about the Geonor instrument and its history and design. The idea for the system first surfaced in 1984 in response to a need to better measure solid precipitation. The first instrument was produced in 1985, and the earliest design employed a three-wire configuration. For cost-savings reasons and because of the longevity of the wires, a one-wire system became standard. Øyvind pointed out that proper installation, antifreeze/oil mixtures, and maintenance routines were critical to ensuring the long-term health of the instrument and measurements. He also referred to typical and known problems with the gauges, including wire breaks, snow in the inlet, and snow in the bucket. Summaries of their possible causes and remediation were also presented.

GEONOR T-200B PRECIPITATION GAUGE



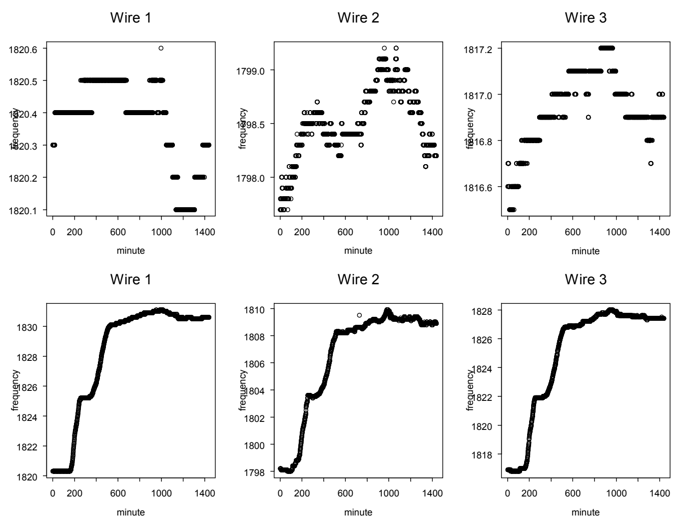
Instrument schematic. The three-wire modification replaces two supporting struts (shown on the left side of the diagram) with additional wire/sensor units to create a three-wire system less sensitive to leveling. (From Geonor.)

VI. Specific studies

Nolan Doesken (Colorado Climate Center, Colorado State University) presented a brief case for the importance of high quality precipitation data for diverse applications. As an example, he presented results from the first year of the National Weather Service ASOS (Automated Surface Observing System) Climate Data Continuity study completed in the 1990s. The study showed that the ASOS heated tipping bucket gauge under-measured precipitation significantly when air temperatures were below the freezing point. The results were quite dramatic and showed an extreme decrease in measured precipitation as a function of colder temperatures when compared to the standard rain gauge or weighing bucket rain gauge. By –10 ºC, the ASOS gauge rarely reports any precipitation at all, even in situations of significant snowfall rates. These results are very troubling for U.S. climatologists as it is now 10 years later and this type of gauge is still used at hundreds of automated weather stations despite knowledge of its chronically poor winter performance. Nolan also pointed out that most users of climatological data are unaware that this problem exists. The work is important in the context of weighing bucket type measurements like the Geonor because in some regions, and certainly during winter, solid precipitation can be the predominant precipitation type.

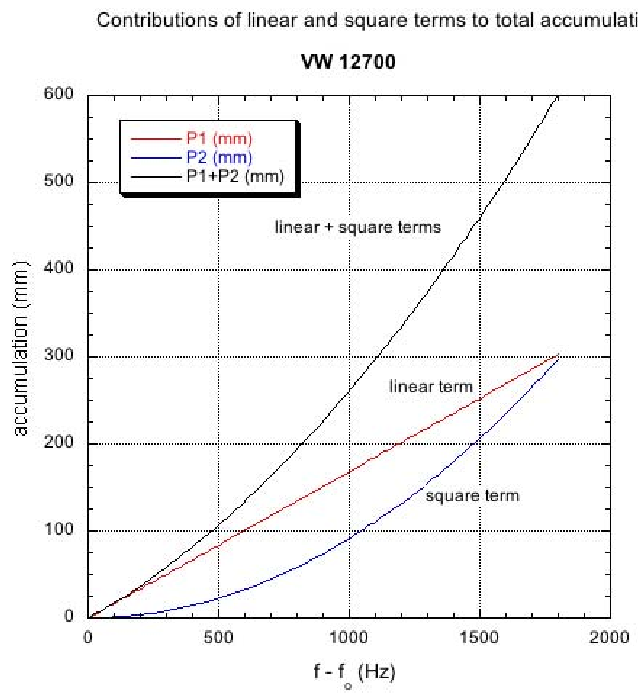
Claude Duchon (University of Oklahoma) showed comparisons of different wind shield configurations used with the Geonor gauge. Appropriate shielding is necessary if accurate precipitation values are to be obtained, particularly during snow events. Claude also reported some results comparing heated and unheated gauges in a double-alter windshield. The heated gauges seemed to report better precipitation values and there were not problems with snow build-up on the inlet or inside the gauge, as can happen with unheated instruments. Claude also reported on results from other issues he has investigated, including the three-wire variation to the instrument as well as wind and temperature effects.

Yves Durocher discussed the performance of the Geonor and the problems with both undercatch and false precipitation reports. Yves also talked about some temperature response studies that Harry Lamb (Environment Canada) had performed on Geonor gauges in the lab. The response was found to change inexplicably when the temperature crossed 0 ºC. He also reported examples of wind siphoning at Paulatuk and Resolute where winds can be very strong.   Last, he showed examples of the daily sinusoidal-like variations, similar to those observed by the Swedes. The variations were sometimes out of phase with temperature changes, so don't seem to be temperature related, and more work clearly needs to be done to understand them.



The top panel shows frequencies from each of the three wires on a day when no precipitation occurred. The bottom panel shows the three wire frequencies on a day with precipitation. For significant precipitation events, it is easy to interpret the variations over time. However, observed small variations occurring during non-precipitation events can be misleading, and longer measurement periods are required to determine whether or not the variations do signal precipitation. Some aspects of the diurnal variability (in the above case, the rise around 1000 minutes) appear common to the three wires, while other aspects (in this case, the behavior at the end of the day) seem to be in opposition. Averaging the frequencies of the three wires will minimize the variation compared to what is observed for a single wire. (From Betsy Weatherhead.)

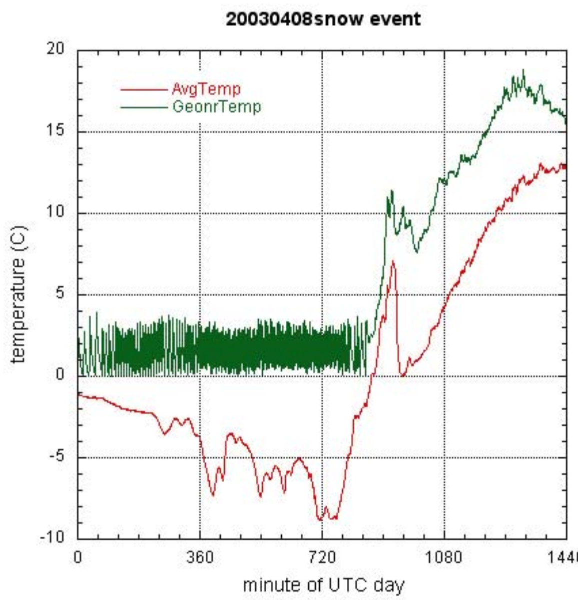
Jody Swenson (Campbell Scientific) provided information on the datalogger in response to reports by Mark Hall of strange wire behavior that was observed in the data. Yves Durocher also reported seeing intermittent drops and strange values in Canada's data record. Jody explains that the datalogger does return a –699 value to indicate possible sensor problems. However, the intermittent nature of the occurrence suggests that other factors such as radio interference may play a role, and testing should be done to resolve this question. Jody also gave more detail on two options for datalogging using the Campbell equipment. There are two different datalogger instructions that can be used to measure the signal from the Geonor T-200 precipitation gauge. The period average (P27) instruction computes the average period or frequency over a user programmable number of cycles, while the pulse count (P3) instruction accumulates the total number of counts over a user programmable time interval. The datalogger can report a frequency accuracy of ±0.03%, which translates to ±0.9Hz or ±0.45 mm, for the period average (P27) instruction.



Change in sensitivity of the frequency measurement as a function of bucket weight. For an empty bucket, the sensitivity is ~0.2 mm per Hz. For a nearly full bucket, the sensitivity is ~0.5 mm per Hz. (From Claude Duchon.)

Mark Hall (NOAA ATDD) followed Jody's overview with results from his own tests exploring the number of cycles and the effects of different wind speeds. The tests suggest that longer averaging times will help filter out some of the noise. Mark also presented results of the precipitation intercomparison study at Bondville, Illinois, where the Geonor was run alongside a tipping bucket. False reports are sometimes observed for the Geonor but not in all wires, suggesting that the three-wire system can provide an advantage for screening out spurious values. Bruce Baker said that it was likely there would also be a plan to add tipping buckets at the CRN sites to help resolve this problem, and Betsy Weatherhead brought up concerns that requiring tipping bucket verification might mean losing knowledge of trace levels of precipitation.

Both Mark Hall and Claude Duchon have explored some options for heating the Geonor. Their methods seemed to have success for instruments in the field. Two aspects discussed involve using a controlled heating mechanism based on temperature or time to avoid any loss from evaporation. Chuck Wade pointed out that snow could possibly stick to the gauge under high wind conditions at temps down to –20 degrees C and that there was probably no temperature cut-off below which heat would be unnecessary.



Gauge heating can help keep the sidewall temperatures above freezing to prevent snow build-up and capping. The heating is temperature controlled to try to minimize additional evaporation. (From Claude Duchon.)

VII. Roundtable Discussions

The roundtable discussions focused on 11 main topics identified as priorities or as areas where further understanding and community consensus is required.

<u>Topic 1—Diurnal Cycle</u>

All users of the Geonor regardless of network or country reported seeing a sinusoidal-like daily variation (in some locations as high as 20-30% of the measured frequency) in their data. Possible culprits include combined effects from temperature, bending of the pedestal, balance of the bucket, solar radiation, deformation of the bucket, electronics, gravity, and dew or frost. There is a need to understand and eliminate variations in the data that are clearly not due to wind pumping. Because this cycle may exist at low frequencies, it is imperative to adequately account for it in obtaining real-time measurements. Longer averaging intervals (greater than 15 minutes) will be essential for achieving real-time, high quality data. Adequate understanding will also assist in identifying trace precipitation amounts.

Current needs:
Quantify the magnitude of problem and determine any seasonal or location dependence.

Approaches:
An algorithm may be sufficient but would need to be implemented in real time. The physics behind the problem need to be better understood as the variations are not necessarily due to temperature and there is likely more than one phenomenon contributing. The three-wire system may be useful in diagnosing this problem by providing information on different parts of the bucket system.

<u>Topic 2—Undercatch and wind effects</u>
Wind can reduce the amount of precipitation collected by any type of precipitation gauge. Significant effort has been devoted to study wind effects and the general undercatch of the Geonor instrument, but the problem is not yet solved. This problem is not uniform across networks because different wind shields are used. Canada and Sweden both currently use a single alter wind shield while the USCRN uses a small double fence intercomparison reference (2/3 diameter DFIR) shield. It is necessary to know the corrections for each wind shield. The corrections depend on the relationship between fall speed and wind speed, which ultimately determine the angle at which precipitation approaches the gauge. Turbulence is also a significant factor.

Current needs:
Correcting these effects is critical to both climatological understanding and real-time monitoring. There is an urgent need to develop appropriate adjustments. Studies have been done on the wind shield configuration and gauge set-up, but these need to be expanded to other locations and should perhaps involve U.S.-Canada co-locations. Timescales of corrections are important, and at certain timescales it may be possible to improve the corrections by using real-time winds. Snow capping and contributions for snow build-up falling into the gauge will need to be taken into account and those events removed before the corrections are applied. WMO data collected in Finland for more than four winters and from other sites are available to be used in determining the wind undercatch of the Geonor gauge.

<u>Topic 3—One wire versus three wires</u>
Some networks use a one-wire configuration of the Geonor gauge while others use a three-wire configuration. In all networks there is an ongoing discussion of which approach is better. The pros of the three-wire system include quality assurance, allowance for non-critical (such as interface card) failures, and smaller variations for a three-wire average. The most significant con of the three-wire system is the increased instrument cost ($500/wire so an additional $1000/gauge). Neutral considerations include the small but constant wire failure rate (more wires mean potentially more failed wires). Unless Geonor is successful in developing a three-wire system that functions satisfactorily when a wire breaks, maintenance and service costs may triple, from 2 to 3

corrective maintenance per year, to as many as 6 to 9. If Geonor succeeds with the wire redundancy, then maintenance due to wire breakage would decrease.

Recommendations:

- Explore quality assurance possibilities.
- Quantify the gain in information possible from three wires and balance the outcome of pros and cons.
- Explore the diurnal cycle and false reports from a three-wire perspective.
- Because Canada and possibly Sweden are currently considering testing some three-wire gauges, continue to follow up on their results and decisions.

Topic 4—Bucket contents

Oil and antifreeze are added to the collection bucket to prevent evaporation and freezing. The oil and antifreeze amounts may vary by season and location, as is currently the case for Sweden's network. In summer, the Swedish network uses 0.4 L of hydraulic oil to prevent evaporation from the bucket. In winter, the mixture used at northern sites is 0.4 L hydraulic oil, 2.4 L glycol, and 3.6 L methanol. The winter mix for southern sites is 0.4 L hydraulic oil, 1.7 L glycol, and 2.5 L methanol.

Canada uses no ethanol but does use oil and ethylene glycol. They are still exploring optimal mixtures. The U.S. uses propylene glycol with 10% water (as recommended by NWS) but no oil because of environmental disposal issues. In the summer, the USCRN will likely use no antifreeze at southern locations but this is still being examined. Geonor offers a formula, which is the mixture used by the Swedes and is reported to work well.

Removal and proper environmental disposal of the oil and antifreeze are an issue for everyone. Certain components can be environmentally toxic, but finding an acceptable mixture is necessary to obtain accurate measurements not affected by evaporation or by freezing the bucket contents.

Geonor is currently working to produce an 850-mm gauge and possibly a 1000-mm gauge. These increased gauge capacities will be very useful in high precipitation regions where buckets can fill more quickly.

Other bucket issues include unwanted additions to the buckets. Birds can get into the bucket but are generally large enough to detect. There may be dust or other debris that could go into the bucket gradually and these additions may be difficult to detect. Multi-type precipitation measurements (for instance, an optical sensor) may be needed to address this problem.

Recommendations:

- Explore more environmentally friendly oil/antifreeze mixes. (Geonor reports that there need not be a standard formula: the important aspect is that the specific gravity of the mixture is near that of water.)

Topic 5—Heating

There is a need to revisit the WMO recommendation never to heat a precipitation gauge. It is not clearly understood whether or not their recommendation applies only to tipping buckets. There is clear value in heating but the issue is neither simple nor solved.

Heating is only critical for solid precipitation measurements. Evaporation (primarily from sidewalls) and "chimney" effects, in which warmer air rises above the surrounding cooler air, causing an updraft and possibly deflecting some precipitation from the gauge orifice, are still issues. Controlled and intermittent heating seems to be the best solution. This type of control may require the temperature of the sidewalls to be carefully monitored. An additional weather sensor may provide information on whether or not precipitation is occurring, which could be useful in determining when to begin heating.

Power and power availability are a concern—not all sites have sufficient electricity.
Recommendations:

- Further studies are needed to determine the potential benefits of gauge heating and to best balance the advantages for solid precipitation measurements against potential loss from evaporation.

Topic 6—Datalogging

Currently the U.S. and Canada use the Campbell Scientific datalogger to obtain Geonor gauge values. The Swedes use the Vaisala. Understanding datalogging is critical to understanding precipitation measurements. Multiple options need to be explored and choices need to be made. The datalogging uncertainty is likely to be very small but an uncertainty estimate is needed.

Current needs:

Spurious values are observed from the Campbell datalogger. These may be solved in the coming weeks. There is a need to determine whether –699s are occurring as a result of a sensor problem or could be attributed to radio interference. Determining how to minimize datalogging uncertainties and obtain the highest quality data possible remains an issue. Campbell Scientific will provide a one-pager on the datalogger and recommendations for best reporting.

Topic 7—Data Quality Evaluation

The procedures depend on application, whether for forecasting or climate quality. The Swedes have quality evaluation routines that have been developed and are stable. Canada and the U.S. are still developing procedures. Quality evaluation is a critical aspect for data integrity.

Recommendations:

- Quality evaluation will require further research and cross-network communication.
- Comprehensive documentation including meta-data must also be included.

Topic 8—General Set-up

Set-up instructions are detailed in the Geonor manual and are important for data quality. Improper leveling or vibrations can result in bad data or in wire breakage. Weak supports may contribute to diurnal variations.

Recommendations:

- Assess the magnitude of the problem and options for improvement. Options include wrapping the pedestal, and measuring to make sure there is no tilt in the instrument. Other specific actions may be pedestal and location specific.

Topic 9—Failures

There are both critical and non-critical types of failures. In a non-critical failure, the data can still have value. Wire breakage is the most common failure observed. For both one-wire and three-wire systems, a wire breakage is a critical failure.

The Swedes have had only 5 failures in 7 years operating 104 instruments on Geonor 1-meter pedestals. All 5 failures were wire breakages. Canada has had no failures thus far. The USCRN manufactured their own pedestal and report 6 wire breakages in 265,000 gauge hours. Some breakages were also reported at the Marshall test site but it was pointed out that the area often experiences very high (100 mph) winds.

The causes of most, but not all, wire breakages are understood and can be minimized with good oversight. Possibilities were discussed for salvaging data after a wire breakage. If a wire does break in the three-wire system, it can be replaced or a chain added and total precipitation will still be obtainable.

Current needs:

It is necessary to achieve a more complete understanding of all possible failures. For quality assurance issues, it is important to identify failures that could still allow data to be reported so that the data can be corrected or flagged.

Recommendations:

- Geonor may explore the possibility of modifying the transducer support mechanism to obtain good observations with only two wires (insuring that a wire breakage is not a critical failure).
- It is important to write up proper oversight to minimize wire breakages.

Topic 10—Calibration/Verification

The Swedes verify the “empty” bucket vibration frequency, f_o, in the field after checking the value in the laboratory. The U.S. does the same thing and stresses the value of both lab calibration and field checks. No major differences are reported between the manufacturer and the lab calibration. Mark Hall reports that the factory calibrations agree exceedingly well with the NIST-traceable calibrations. The Swedes also report that the factory calibration transfers well to the field for specified temperature ranges.

There is a reported temperature dependence of the sensor, which is generally calibrated for an 85 ºC temperature range. The Geonor manual provides some references addressing this issue and a forthcoming paper will present results based on 18 years of data.

The Swedes have looked for and not seen any calibration drift over 7 years. NCAR reports no drifts, with changes of only +/- 0.5% over 3 years. The USCRN has systems in place to monitor for long-term drift.

Current needs:
Temperature effects on actual measurements need to be verified. It would be useful to do some tests over a large temperature range (a –45 to 40 ºC range would be the minimum desired), with 6 to 10 or more sensors.

Topic 11—Maintenance Routines
The Swedes do maintenance on each instrument once per year and have a local technician for other maintenance as needed (for example when a bucket needs to be emptied or fluids need to be switched). Canada is attempting a minimum of two maintenance visits per year for each instrument to address winter charging and other issues. Geonor recommends at least two visits yearly. The USCRN has one maintenance visit per year plus local support. There is a possible maintenance plan being developed that would include monthly or as needed maintenance. It is important to distinguish that there are two types of maintenance: facilities-type maintenance requiring no technical expertise, and then regular technical visits.

Recommendations:
- Maintenance is important and maintenance people must be trained.
- Standardization and documentation are necessary aspects.

VIII. Identified Priorities

Priorities were established with only network representatives and scientists present, following the dismissal of the instrument representatives. The priorities identified as needing to be addressed within the next 12 months include the following:
- quality assurance
- datalogging questions
- the possibility of instrument co-locations (U.S./Canada/Sweden)
- complete characterization of the system to really understand the measurement
- better understanding of diurnal variations
- improved understanding of wind undercatch and appropriate corrections

IX. Action Items

The first action item relates to developing a communication mechanism. Ensuring continual communication will require a two-fold approach.

A. Designate group leaders on key issues:
   - Diurnal variations—Yves Durocher
   - Wind undercatch/correction—Craig Smith
   - Data uncertainty—Mark Hall
B. A possible follow-up meeting will convene next year. Participants will re-evaluate the need for a follow-up meeting in 6 months.

The second action item relates to informing WMO that their recommendation to never heat precipitation gauges is being revisited. Betsy Weatherhead has already been in discussions with WMO's group addressing climate monitoring issues and will follow up on this item.

Appendix 1 Contact information of meeting attendees

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